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THE BALLISTIC AND MECHANICAL PROPERTIES OF POLYMERS

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I. INTRODUCTION

Transparent armor for applications such as vision blocks, wind screens, and face shields rely on polymers either completely or as a part of a ceramic-plastic composite. Transparent polymeric armor systems are not currently as efficient on a weight basis as opaque armor systems. This work was undertaken to find ways to increase the efficiency of polymeric armor systems.

Orientation and processing variations are known to have a large effect on the static mechanical properties of polymers and spurious data have indicated increases in ballistic resistance for hot stretched homogeneous armor. The influence of hot stretching and other processing variables on ballistic resistance were studied. The effect of orientation on fracture surface energy was studied in some detail to provide insight into the fundamental processes involved in polymer failure.

It would be highly desirable to be able to correlate ballistic behavior with the material and physical properties of the polymeric system to enable rapid predictions of ballistic resistance as well as to lead to improved transparent armor. Up to the present time no such correlation has been known. It was one of the purposes of this study to determine what properties, if any, would consistently be indicative of the ballistic strength of the polymer.

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II. INFLUENCE OF PROCESSING VARIABLES

A study of the effects of orientation, thermal treatment, and water content was carried out to establish the effects of processing variations on the static and ballistic behavior of polymers. The effects of orientation and gamma irradiation induced crosslinking on the fracture surface energy calculated by direct measurement of energy input to a growing crack was studied. Dramatic changes in the static rate mechanical properties occurred (see Table I) but the magnitude of those effects was not carried over to the ballistic resistance.

Hot stretching of a wide variety of polymers was attempted. Various polymers were hot stretched at temperatures in excess of the glass transition. The ease of hot stretching was found to vary widely both because of chemical decomposition (e.g., polysulfone) and necking behavior (e.g., polypropylene). Polycarbonate, poly (methyl methacrylate), XT-500, polystyrene, and polyphenylene oxide were successfully hot stretched.

Samples of the hot stretched polymers were tested for ballistic and mechanical properties at the U. S. Army Natick Laboratories. The existence and extent of orientation of the hot stretched polymers were established by means of optical birefringence. Fracture surface energy was determined by direct measure of energy input to a stable fracture in a triangular cross section bending sample(1). The fracture energy for biaxially oriented polystyrene as a function of degree of hot stretching is shown in Figure 1. Figure 2 shows the results of gamma irradiation on the fracture energy of biaxially oriented polystyrene. The large anisotropy induced by orientation is apparent in Figure 1. Inhomogeneous orientation can degrade the ballistic performance of polymers by introducing planes of low fracture surface energy which leads to splitting and lath-like failure of the plate. Homogeneously oriented polymers did not show any change in ballistic resistance compared to the non-oriented state when tested with a .22 cal fragment simulator.

Stretched polymers do perform better when utilized in composite armor as back up plates for ceramic materials. The reason for this difference in behavior is most likely due to the increase in toughness in the plane of the plate exhibited by oriented polymers. In the case of direct interaction with a missile, the armor plate experiences large shear stresses under the missile, while for a back up material the stresses are largely tensile acting in the plane of the plate.

When stretched polycarbonate is used as a back up plate in a glass-polymer transparent armor system, weight savings on the order of 15 percent can be achieved. Further weight reductions are possible through optimization of design of composite armor systems.

Polycarbonate samples were quenched from above the glass transition, annealed below the glass transition, and held at 90°C in both very low and very high humidity atmospheres. None of the treatments gave rise to detectable changes in the ballistic properties of polycarbonate, when tested with a .22 cal fragment simulating projectile. Oriented poly(methyl methacrylate) samples were water saturated and dried in controlled temperature and humidity conditions. No changes in the ballistic resistance was observed even though large changes in the static rate properties have been reported by Ender(3) for similar treatments. The insensitivity of the ballistic resistance to the treatments described is somewhat surprising in light of the large changes which occur in static properties. The insensitivity to mechanical state also implies an attendant large dependence of the ballistic resistance on the fundamental building blocks of the polymer rather than the details of their arrangement.

III. TRANSITION TEMPERATURE CORRELATION

An extensive search for a correlation between material properties and ballistic resistance was conducted in order to provide direction in the development of new materials for armor use. In the course of this search, several suspected pertinent properties were investigated. Table II shows a sample of these variables. No real correlation was found to exist between the ballistic properties and the properties shown, as with all other commonly observed properties.

Several investigators, notably Nielson(4), Matsuoka(5,6), and Boyer(7), have hinted that in order for a polymeric material to have good impact strength, it must have at least two transitions, one occurring above ambient temperature (the glass transition temperature, T_g) and one below ambient temperature (a "brittleness" temperature). Figure 3 and Table III give the results obtained when such a correlation is attempted in terms of the relative difference between the upper and lower transitions.

As can be seen from the graph, the correlation is remarkably good. It shows that as the spread between the two transitions increases, the better the polymer performs ballistically. For the first time a property is known to exist which can predict ballistic performance.

A low temperature transition in a glassy amorphous polymer is not in itself indicative of good impact behavior. It appears that this transition must be specific in its source; e.g., preliminary data show that the low temperature transition must be caused by motion in the main chain of the polymer, not by side group movement. This restriction is not necessarily adverse. It can be quite useful from a molecular standpoint, resolving hitherto controversial transitions into main chain or side chain motions.

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The most exciting aspect of the transition temperature correlation is that it obviously depends on molecular parameters such as chain stiffness. That thermal and mechanical behavior for a polymer should be so intimately connected opens new vistas of investigation. Parameters such as chain stiffness and glass temperatures, calculable from first principles, have ultimate influence on the behavior of bulk polymer systems. Screening of candidate polymer armors by simple thermal measurements as well as prediction of the effects of molecular changes on the ballistic resistance should now follow. The correlation should allow for the synthesis of new polymers designed specifically for high impact resistance.

IV. CONCLUSIONS

We have studied the effects of hot stretching induced orientation on fracture energy and found large changes both perpendicular and parallel to the orientation directions. Orientation does not improve the ballistic resistance of homogeneous armor but can increase the efficiency of composite armor. Processing variables such as thermal history and relative humidity at working temperatures were shown to have little effect on the ballistic resistance of polymers, a fact which is important in design considerations as well as from a theoretical standpoint.

The establishment of the relationship between thermal and ballistic properties is of great importance both from the point of view of the armorer in the selection of materials and for the polymer physicist and synthetic polymer chemist in their understanding of the processes that occur in polymers as well as in the molecular design of materials to accomplish specific tasks. The backbone composition of the polymer molecule was demonstrated to be of overwhelming importance in comparison to the more delicate configurational changes induced by processing of the bulk polymer.

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TABLE I
Effect of Uniaxial Elongation on Physical Properties of Polymers

Polymer	Relative Fracture Strength	Relative Extension Modulus
Polystyrene(2) parallel to orientation (100% elongation) perpendicular to orientation	1.2 0.5	1.2 0.5
Poly(methyl Methacrylate)(2) parallel to orientation (100% elongation)	1.25	-
Polyethylene tetrathalate(3) parallel to orientation (High elongation) perpendicular to orientation	- -	17.8 0.67
Nylon 66(3) parallel to orientation (High elongation) perpendicular to orientation	- -	19.2 0.67
Polyacrylonitrile(3) parallel to orientation (High elongation) perpendicular to orientation	- -	5.8 0.67

TABLE JI
Ballistic Performance vs Material Properties

Polymer	V ₅₀ (ft/sec)	Izod Impact (ft #/in. of notch)	Flex Modulus (psi x 10 ⁵)
PPO	1250	1.5 - 1.9	10.5
Polysulfone	1130	1.3	3.8
Noryl	1120	1.3	3.6
Polycarbonate	980	12.0 - 17.5	3.4
Nylon (6-6)	1000	1.0 - 2.0	1.8 - 4.1
Polyurethane	930	No Break	3.2 - 3.5
Nylon 6	930	1.0 - 5.5	1.4 - 4.0
PMMA	600-900	0.4 - 0.5	3.9 - 4.7
PCTFE	680	2.5 - 2.7	---
Polystyrene	580	.25 - .40	---
Teflon	470	3.0	---

TABLE III
 V_{50} Ballistic Limits of Polymers
 (17 Grain Fragment Simulator 0° Obliquity 30 oz/sq ft Areal Density)
 and Corresponding Transition Temperatures

Polymer	V_{50} (ft/sec)	$T_b(1)$ °K	$T_{HD}(2)$ °K	T_b/T_{HD}
PPO(3)	1250	103(4)	464(4)	.22
Cyclooy 800(5)	1130	--	394(4)	--
Polysulfone	1130	172(4)	447(4)	.38
Noryl(6)	1120	127-130(7)	403(4)	.32
Surlyn A(8)	1030	166(9)	311(4)	.53(9)
Polycarbonate	950-1010	172(4)	410(4)	.42
XT-500(11)	1000	188(12)	359(12)	.52
Nylon (6-6)	990-1010	148(10)	330(10)	.45
Polypropylene	940	178(10)	275(10)	.64
Polyurethane	930	140(10)	310(10)	.45
Nylon 6	930	148(10)	330(10)	.45
Celcon, Delrin(13)	820-880	233(4)	383(4)	.61

TABLE III (cont'd)

Polymer	V_{50} (ft/sec)	$T_b(1)$ °K	$T_{HD}(2)$ °K	T_b/T_{HD}
ABS(14)	850	---	372(4)	---
PMA(15)	600-900(16)	313(14)	375(4)	.83
CTFE(Kel-F)(17)	680	248(10)	320(10)	.78
Polystyrene	580	333(4)	372(4)	.90
TFE(Teflon)(18)	460-480	---(19,10)	150-180(19,10)	1.0(19)

Notes on Table:

- (1) - Brittleness Temperature
- (2) - Heat Distortion Temperature at 264 psi fiber stress
- (3) - Polyphenylene oxide
- (4) - Values obtained from 1968 Edition of Modern Plastics Encyclopedia, McGraw-Hill Publishing Co., New York City, New York
- (5) - Marbon's combination of ABS and polycarbonate
- (6) - Modified PPS(3)
- (7) - Value obtained from direct communication with G.E.
- (8) - DuPont's Ionomer
- (9) - T_b reported as less than 166°K
- (10) - These values obtained from Wada, Y., "Mechanical Dispersions and Transition Phenomena in Semi-crystalline Polymers", J. Phys. Soc. Japan, 16, 6, June 1961 (1226). The T_b is here a low temperature amorphous transition. The T_{HD} is really T_g , but the values are very nearly the same.

TABLE III (cont'd)

- (11) - American Cyanamid combination of FMA and a rubbery phase
- (12) - Obtained from dilatometric data obtained from direct communication with American Cyanamid
- (13) - Polyoxymethylene
- (14) - Poly(acrylonitrile-butadiene-styrene)
- (15) - Polymethylmethacrylate
- (16) - Wide variation in ballistic data believed to be due to processing and fabrication variables
- (17) - Polychlorotrifluoroethylene
- (18) - Polytetrafluoroethylene
- (19) - Values obtained from Wada did not show any amorphous transition other than the T_g .
Therefore, the ratio becomes $T_g/T_g = 1$.

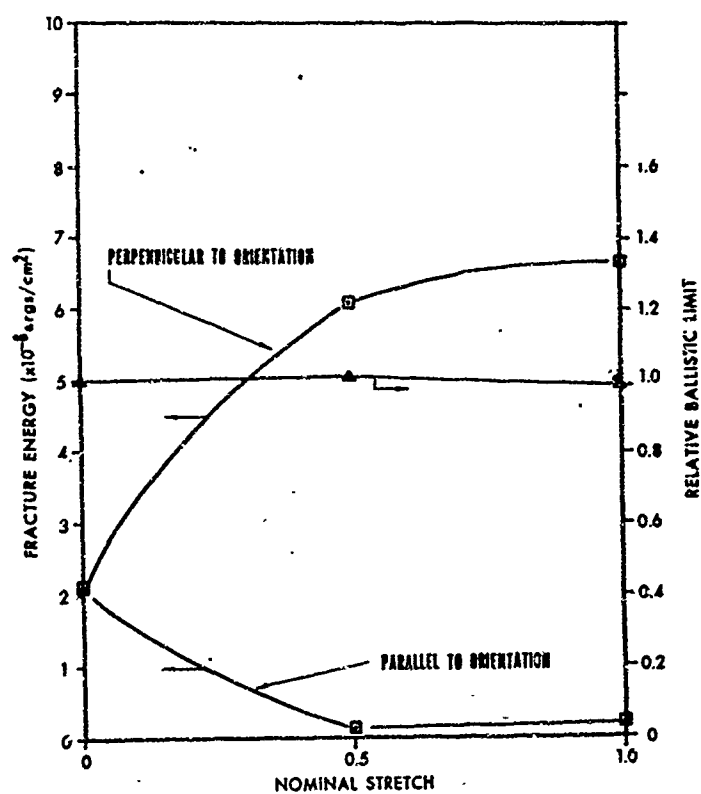


Figure 1. The fracture energy and relative ballistic limit of biaxially oriented polystyrene

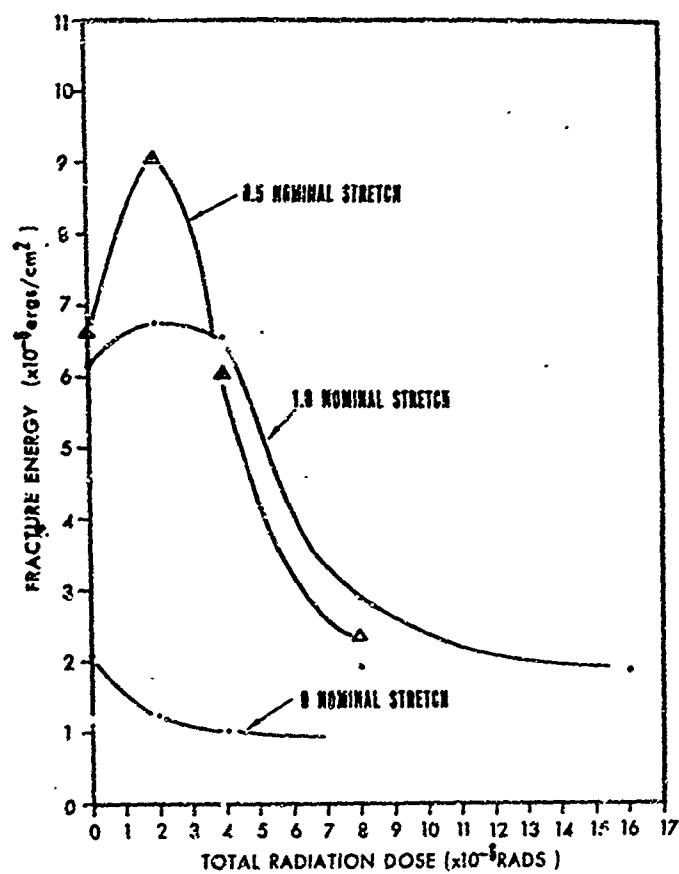


Figure 2. The fracture energy of biaxially oriented polystyrene in the orientation direction as a function of gamma irradiation dose

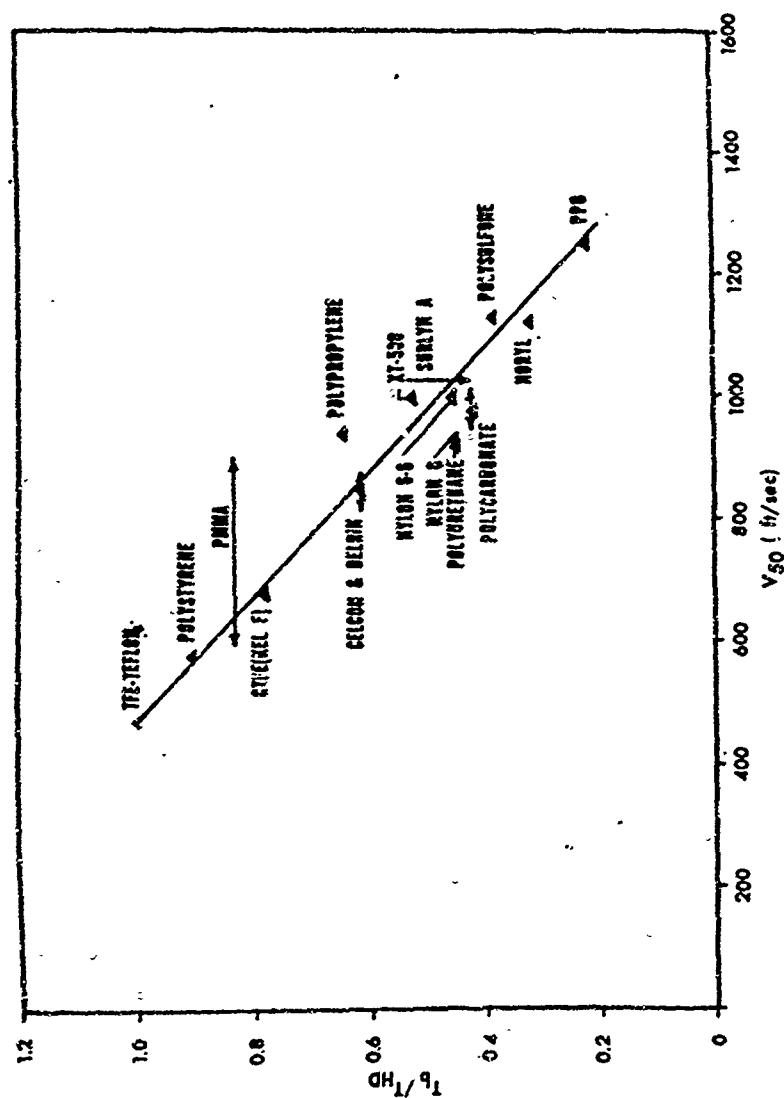


Figure 3. The relationship of the ratio of brittleness and heat distortion temperatures to the ballistic limit at constant areal density (30 oz per square foot of various polymers)